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Technical Report #12

The Dynamics of Off-grid Lighting Adoption

Field Study Methods and Results from a 2008-2009 Market Trial of Night Market Vendors in Rural Kenya

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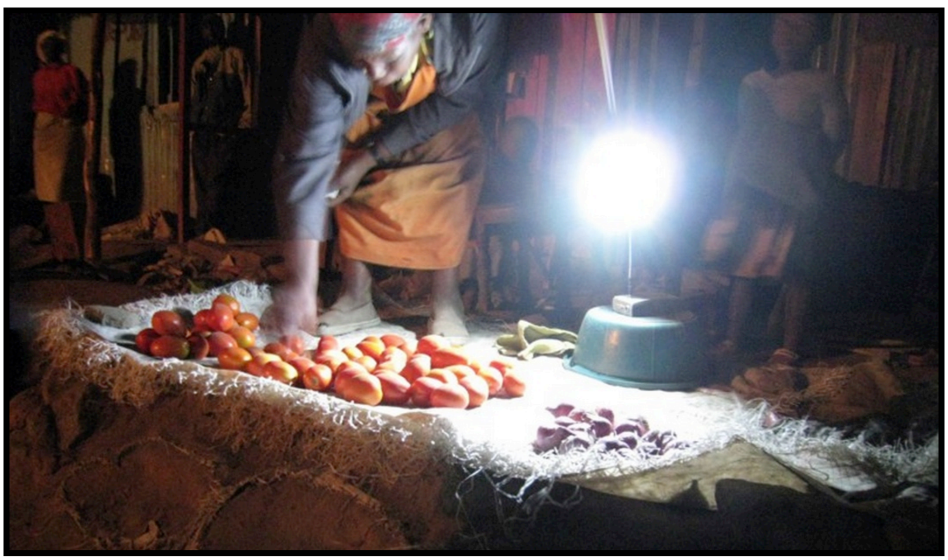

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The Lumina Project—an initiative of the U.S. Department of Energy's Lawrence Berkeley National Laboratory—provides industry, consumers, and policymakers with timely analysis and information on off-grid lighting solutions for the developing world. Lumina Project activities combine laboratory and field-based investigations to ensure the formation of policies and uptake of products that maximize consumer acceptance and energy savings. For more information, visit http://light.lbl.gov

Introduction and Summary

The market for improved off-grid lighting has rapidly developed in recent years, from a nascent and emerging set of solar-LED lamps to a big business with several million products being sold annually (Dalberg Global Development Advisors 2013). Replacing fuel-based lighting with rechargeable, efficient lighting can provide higher quality, less expensive lighting services to end-users (Radecsky et al. 2008; Mills and Jacobson 2007; Brüderle 2011; Johnstone, Jacobson, and Mumbi 2009), reduce health risks (Lam, Smith, et al. 2012; Apple et al. 2010; Mills 2012), and mitigate the greenhouse gas impact of lighting technology use (Mills 2005; Lam, Chen, et al. 2012). As the market develops, critical questions about the way to appropriately measure impacts of improved lighting on peoples' lives remain.

This study summarizes work that was completed in two small towns in Kenya circa 2008-2009—the "early days" of the Kenya solar-LED market—to understand the dynamics of adoption. The methods we used combine social geography with energy and technology analysis to understand LED lighting adoption patterns in the context of a market that is getting its first exposure to LED technology, a situation that is repeating itself in villages and towns across the developing world.

Our findings fall in two categories and are summarized here:

1. Research Methods Findings – our study was a testing and development ground for a range of field methods that can inform ongoing efforts to measure impacts in the market:

a. **True cost of kerosene** – The cost is closely linked to world oil prices but includes additional contributions from geographic scarcity (higher prices in rural areas where there is little competition on a hyper-local, block-by-block basis).
b. **Measuring fuel consumption** – We employed a range of techniques to measure baseline fuel consumption and find that high frequency surveys of kerosene expenditure *combined with reliable information on the true cost of kerosene* are a useful and relatively accurate way to estimate consumption and expenditures. Alternative methods for measuring consumption include rigorous (and expensive) field monitoring of mass balances for kerosene and historical recall surveys; we compare the results from each method.
c. **Embedded data-logging** – We deployed and monitored detailed use patterns of LED lights. The method is promising for understanding peoples' use patterns and the driving factors for operating under conditions of energy scarcity.

2. Market Dynamics Findings – the results of the study provide key insights in the dynamics of lighting technology adoption:

a. **Diversity of baselines and impacts** – Off-grid lighting users have diverse patterns of use and needs for light. Even among the relatively homogeneous population we worked with, night market vendors, there is wide divergence in the baseline use of fuel and impact of LED lighting adoption.
b. **Willingness to pay** – Of 23 night vendors to whom we offered LED lanterns at realistic market prices, 14 (61%) opted to purchase (cash [5] or financing [9]), albeit under unique circumstances of participating in a long-term field study. They were offered a single style and model of lantern, with technology of a late-2000's vintage. Uptake could well be

higher at present with contemporary technology options and through more familiar supply chains.

c. **Kerosene not completely eliminated** - People who adopt improved lighting do not universally eliminate kerosene consumption (some even increased consumption from the baseline). This is because people may continue to use their fuel-based lighting product(s) in addition to their new LED lighting products. The LED lighting adopters in our study achieved a mean reduction from the purchase-time baseline of ~50% (and substantially more if compared to rising use among non-adopters). Moreover, a 50% drop in kerosene prices during the time of the study induced non-adopters to increase their kerosene use by 70%, whereas the adopters achieved significant absolute reductions. Notably, about 60% of adopters eliminated all kerosene use for lighting. Several adopters noted the benefit of LED lighting in eliminating their exposure to fuel price volatility. Higher-brightness products may achieve greater offsets, and other studies indicate more successful conversion rates with more modern technologies.
d. **Market spoiling from low-quality LED products** – We observed a strong and statistically significant market spoiling impact of exposure to low-quality LED flashlights on peoples' choice to purchase better quality LED task lights. People with prior exposure to low-quality products were much less likely to purchase LED products in general.

Research Approach

The population we studied was night market vendors who operate in two towns in the Rift Valley Province, Kenya and rely on off-grid lighting to illuminate their businesses. After conducting an initial baseline survey of 50 vendors, we made detailed measurements for a subset (n=23) of them and offered the subset the opportunity to purchase an LED task light, with or without solar charging. Fourteen chose to purchase the LED task light. One purchased the optional solar panel (others opting to recharge through local phone-charging enterprises).

In a previous report we focused on the baseline economics of off-grid lighting for the study group and documented many of our field methods for measuring fuel-based lighting use (Radecsky et al. 2008). We also documented qualitative user feedback and the demand for lighting service (Johnstone, Jacobson, and Mumbi 2009; Alstone, Jacobson, and Mills 2010).

This report documents the overall methods we developed for measuring the dynamics of off-grid lighting adoption and findings on the dynamics of the early market for LED lighting in Kenya. The outcomes from this work are relevant for scoping the next generation of market monitoring and evaluation efforts to track global progress on energy access (e.g., the Sustainable Energy for All *Global Tracking Framework* (SE4ALL 2013)) and other institutional and private sector efforts to catalyze markets and measure impacts for improved off-grid lighting.

Geographic and population details

The night market vendors we studied live and do business in the towns of Maai Mahiu and Karagita (Figure 1). Both towns are located in Kenya's Rift Valley Province, and at the time of the study were each populated by approximately 8,000 residents. Maai Mahiu is a crossroads town, and provision of goods and services to passing travelers and truck drivers is an important economic driver there. The town is dispersed over a large area, encompassing about 3 km^2, and has a market area centered on the intersection of highways that link the cities / towns of Nairobi, Naivasha, and Narok. Karagita is more isolated and compact than Maai Mahiu, situated on an approximately 1 km^2 area in between the industrial greenhouses and flower farms that line the shores of Lake Naivasha. The flower farms are the main source of income for Karagita residents, as many of them work at the farms. The people in Karagita are generally less prosperous than those in Maai Mahiu, owing to their reliance on relatively low-wage labor as opposed to the more diverse trading and service economy of Mai Mahiu.

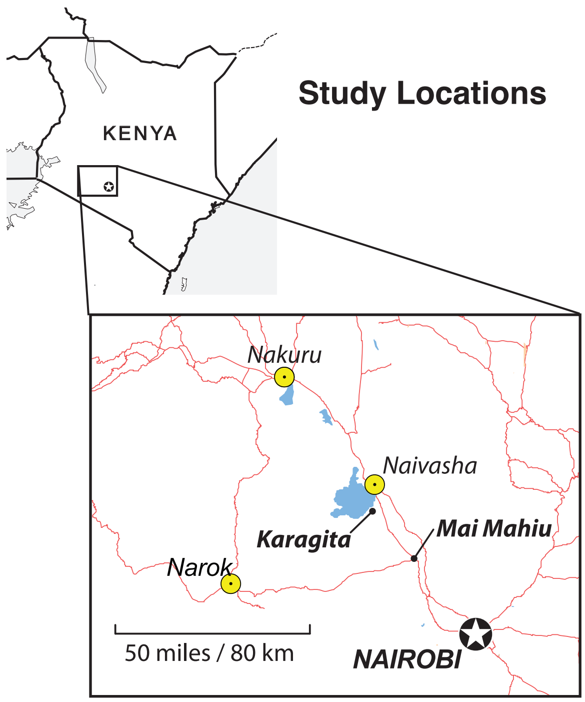

Figure 1: Location of the field study sites, Mai Mahiu and Karagita.

Field Methods Approach

The goal of our market study was to measure the economic and environmental effects of efficient, LED lighting technology adoption by users of fuel-based lighting. To ensure that people who adopted (bought) LED products in our study were representative of the early adopters for the technology, we chose a "market-based" approach (i.e., we offered products to people at realistic market prices) as opposed to a giveaway. We chose to focus on night market vendors because they are relatively easy to access at night for observations and measurements, they have an income that might allow them to be early adopters of LED lighting, and they have a business incentive to adopt lighting that is less expensive to operate and more eye-catching for customers. While those characteristics made night market vendors a good target population for this initial work, their unique needs (e.g., lighting so customers can see their wares, lighting to attract customers from the street) means that their choices related to lighting technology are not necessarily broadly applicable to the general population.

To establish a baseline, we first surveyed 50 vendors (25 in each town) on their access to lighting and their knowledge base about emerging LED products. Next, we identified a subset of 23 of those vendors and made detailed measurements of their baseline kerosene consumption for lighting. This was an opportunistic sample of vendors who were both amenable to having us make measurements each night and who maintained a fixed shop location that our research team could find night-to-night. We developed a host of techniques to characterize the baseline kerosene consumption patterns for the subset of 23 vendors that we focused on; they are described in detail in Radecsky et al. (2008). In brief, in one method we used successive measurements of lamp mass over an evening of use to estimate the burn rate of lamps, and measured the lamps the following morning to estimate the total kerosene consumption. As a second method we repeatedly asked vendors to self-report how many hours they used their lamp(s) and how much kerosene they purchased on a daily basis. For each vendor, we collected at least one week's worth of data in this manner. These data were complementary to the survey questions we asked about typical use patterns. Those 23 vendors were each offered an LED product at market prices, and 14 of them (61%) chose to purchase one. The LED products we offered for sale were gooseneck task lights with two charging options: solar and grid. The lamp with its associated solar module is pictured in Figure 2.

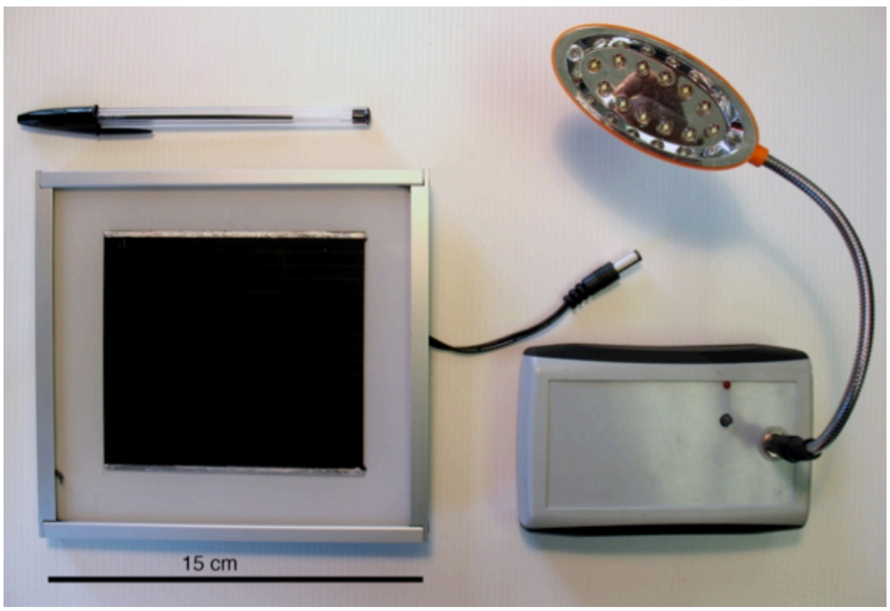

Figure 2: Gooseneck lamp and solar module offered for sale in the study. The AC-DC recharging circuit ("wall wart") that was available as an alternative to solar charging is not pictured. The pen is shown in the picture for scale.

After six months and again after one year, we conducted follow-up surveys with 20 and 18 of the subset of 23 vendors, respectively (three vendors were unavailable at six months and five at one year). The follow-up surveys replicated the baseline survey questions related to lighting use and included some user-satisfaction and habit information for those that chose to purchase an LED product. Throughout the year, we offered a full warranty to the LED lamp users to ensure that durability issues were not the limiting factor in their choice to access LED lighting or not. One member of the research team is a solar energy technician and longtime resident of the area who has social connections to people in both towns. He was available throughout the study period to provide technical support and maintenance.

Integrated data-logging

The lamps we sold had embedded data-loggers that were custom-developed by our team for monitoring patterns of use (pictured in Figure 3). Unfortunately the data-loggers were early versions and were fraught with problems that limited their effectiveness and resulted in significant periods of missing data. However, we were able to monitor lamp use patterns for 350 days in total between the 14 vendors over a six-month period (out of a potential 2,500 days of monitoring). The data we obtained were not useful in the end for making assessments of overall cost of ownership but provided a first-order check on the survey responses from vendors about their frequency of charging and typical use patterns, and revealed other interesting aspects of usage patterns.

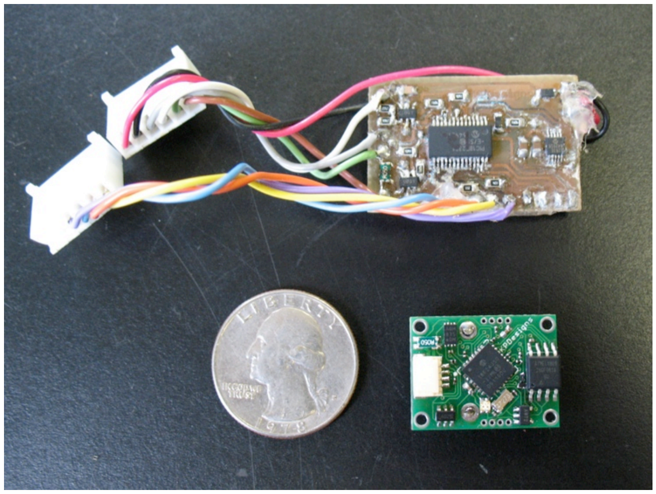

Figure 3: Two versions of integrated data-loggers. The top (larger) version was used in this study. Based on experience using the devices and incremental improvements, we and our colleagues developed a second version pictured below that can be used in future research and proved to be more reliable than the first version.

The data loggers we used monitored battery voltage and current at a sampling frequency of one minute. From the data one can discern solar or grid charging modes during the day and patterns of use at night (and in the early mornings). The data were stored onboard the device and retrieved via USB connection by a research assistant who visited participants during the course of the study. The loggers were powered by an onboard primary battery (i.e., they did not consume power from the lamp). In contrast, as one would expect, contemporary off-grid energy systems with onboard computing and/or communication (e.g., pay-as-you-go systems) do consume a small amount of the available energy as a background load.

An example of the data stream we observed is in Figure 4. With careful analysis (automated in a data processing script) one can discern users' effectiveness of solar charging strategies, patterns of energy use, and responses to energy scarcity (a low battery).

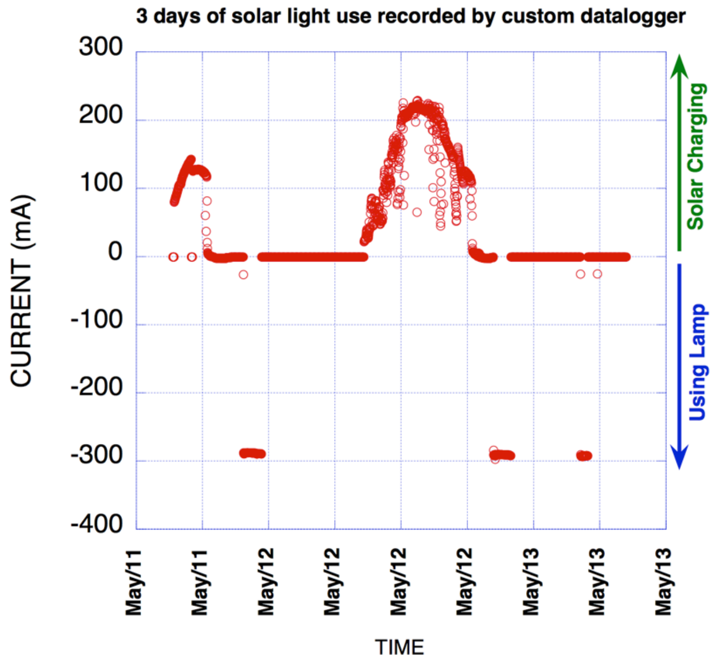

Figure 4: Example data stream for monitoring LED task lighting.

True cost of kerosene

One key to our analysis was measuring the true cost of kerosene to the night market vendors who work in Karagita and Maai Mahiu. The value can be used to estimate the operating cost for fuel-burning appliances with a known burn rate or to estimate the total amount of kerosene consumed by people who self-report the amount they spend on fuel.

The vendors predominantly purchase their kerosene from owner-operated storefront pumps that are located in the market centers; the pumps have pushed out smaller operations that were previously ubiquitous (e.g., those who use a dipper or pre-measured soda bottles to sell) (Figure 5). We measured the unit cost of kerosene by purchasing small, typical quantities (from 10-50 Kenyan Shillings (Ksh)) from the local vendors then measuring the volume we received with a graduated cylinder. We worked with local research assistants who made anonymous purchases in the early stages of the survey to ensure the unit price was the same for them as it was for the research team. The true price in units of Ksh/liter can easily be derived from the data. The exchange rate for Kenyan Shillings to dollars during our study period fluctuated from ~65 Ksh/$ in June 2008 to ~75 Ksh/$ in January 2009, stabilizing in 2009.

Figure 5: (left) Line of people to purchase kerosene ("mafuta ya taa" roughly translates to "oil for lamp") in Mai Mahiu at dusk; **(right)** kerosene sellers in Karagita.

Figure 6 shows the seven-year trend for kerosene prices from a highway filling station in the vicinity of Maai Mahiu and Karagita, the measurements we made from the town sellers, and world crude oil prices during the same period for reference. The shaded region on the plot is the study period; during the beginning of our study crude oil prices were reaching a historic peak, over 120 $US/barrel, and fell rapidly through the following year. The impact of the kerosene price spike on the results of our study is not known to us, although the implication is that people may have more highly valued LED alternatives during June 2008 when we offered them for sale, since it occurred during a time of historically high fuel costs.

The cost of "town" kerosene was systematically higher in Karagita than Maai Mahiu; the town prices in Maai Mahiu did not deviate significantly from the highway filling station price. In June 2008 the approximate price in Karagita was 105 Ksh/l and was 80 Ksh/l in Maai Mahiu, 23% lower. Six months later the Karagita price was 80 Ksh/l but the Maai Mahiu price dropped to 65 Ksh/l, 18% lower. The reason for the markup in Karagita is likely its distance from highway filling stations – Karagita is several kilometers from the nearest filling station and there are two within hundreds of meters of the Maai Mahiu market center. The rural-markup phenomenon was later confirmed on a African continental scale in a more recent report by Tracy and Jacobson (2012), where the median urban-rural discrepancy across five countries was found to be 35% (or 46% when population-weighted).

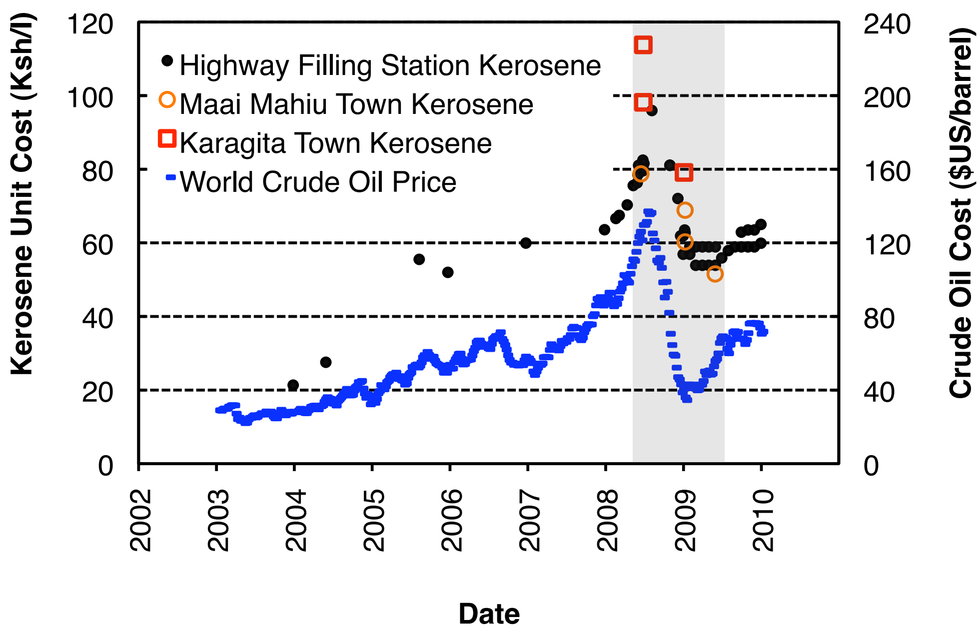

Figure 6: Historical unit costs of Kenyan kerosene and world crude oil from 2003 to 2009; the period of our study is shaded. The Kenyan kerosene prices are from sellers who work in the market centers of Maai Mahiu and Karagita, from whom we purchased kerosene and measured its unit cost, and from highway filling stations near each town. The monthly world average crude oil prices are from (EIA 2012).

Kerosene consumption measurement

In the course of our study, we used three methods to measure the nightly kerosene consumption of vendors at their businesses:

- ***Direct measurements:*** Fuel burn rates were estimated from multiple measurements of the mass of a lamp over each night of use for several days. These were combined with self-reported hours of operation from the vendors. We gathered enough data of this type to make total fuel-consumption estimates for 23 vendors; the data were the basis of an earlier report on the comparative economics of off-grid lighting alternatives (Radecsky et al. 2008).
- ***Record keeping / high frequency survey:*** Vendors tracked the amount of kerosene they had purchased in the previous day and reported to our team daily over a period of several nights. They also tracked the number of hours they used fuel-based lighting in the home and business context. These data were gathered from the same 23 vendors in conjunction with the more detailed nightly measurements described above and combined with unit cost measurements from the local kerosene market to estimate the volume consumed.
- ***Recall survey:*** We included a question to capture the typical amount a vendor spends on kerosene each day in the larger survey (n=50) that we employed and in the two follow-up surveys to a more limited set (n~20) at the 6-month and 1-year points.

We found that the relationship between the approaches to estimating the baseline nightly kerosene use at each business was not uniform, as is shown in Figure 7. The relationship between the survey and record keeping estimates exhibited the best linearity (i.e., internal consistency and agreement), particularly for large estimates. Also, on the low end the relationship was very near unity. If we assume that vendors are well informed about the amount they spend on kerosene each day the record-keeping based estimate could be construed as the most accurate and precise. Based on the relationship we observed between record-keeping and survey-based estimates, we chose to derate all of the survey estimates from the baseline survey by 30%.

Both relationships involving the nightly measurements were linear on the low end and highly scattered for nightly measurement-based estimates above 100-200 ml. The difficulty in estimating overall use based on measuring kerosene consumption rates may stem from the rates being inherently variable based on the operation of the lamp, missing periods of high consumption (like on start up), or spillage.

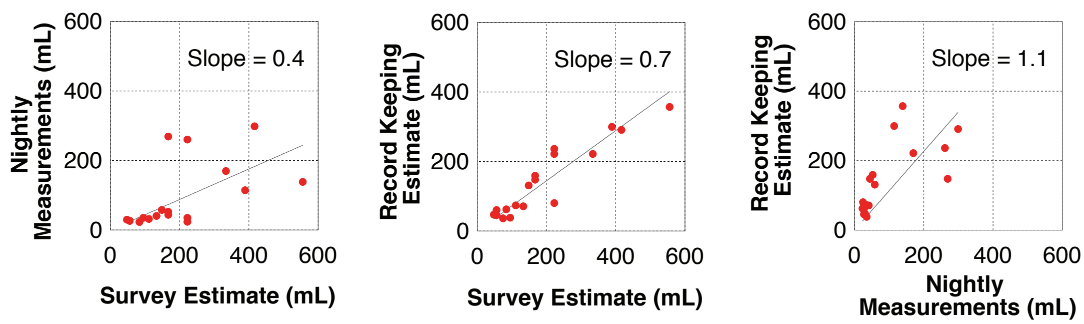

Figure 7: Scatter plots showing the relationship between methods for estimating kerosene consumption in the business context for night market vendors (n=20)

Market Dynamics Outcomes

Baseline Lighting Technology

The vendors we worked with were strategic users of light – it is a costly yet necessary expense for operating their business. They used kerosene burning devices like hurricane, pressure, and tin lamps; candles; and a variety of rechargeable and dry cell electric lighting. Nearly 20% (9 of 50 vendors) used more than one lighting source at their business.

Most of the vendors we surveyed primarily used fuel-based lighting (47 of 50 vendors); those that primarily used electric lighting were special cases (3 of 50 vendors), including one Kinyozi (barber shop) that used a small solar system that powered CFL bulbs and electric razors. Some fuel-based lighting users supplemented or backed-up their lamp with an electric light (normally a flashlight), but 42 of the 47 vendors used exclusively fuel-based lighting in the context of their night market enterprise. Figure 8 shows the types of fuel-based lighting devices used by the vendors in the study and lists the number of vendors who used each type as their primary lighting source.

By far, the dominant lighting technology among the vendors was kerosene hurricane lamps, which were the primary lighting source of 31 out of 50 (62%) of the vendors and the secondary source for two additional vendors. This is in contrast to earlier work by the Lumina Project in western Kenya, where the majority of night market vendors used less expensive tin lamps, which are named after the emptied food tins they that are reformed to create the lamp (Mills and Jacobson 2007). Only one vendor we surveyed used a tin lamp as their primary source of light. Tin lamps provide luminous flux on the order of 10 lm (Mills 2003). Candles were used by two vendors in our study and also produce on the order of 10 lm.

Hurricane lamps, the clear market leader among night market vendors in Mai Mahiu and Karagita, provide luminous flux on the order of 20-60 lm and provide useful lighting service (illuminance) of 3-5 lux at a one meter distance, which translates to approximately 0-10 lux on typical working surfaces (Alstone, Jacobson, and Mills 2010). The median fuel consumption rate of the hurricane lamps we made detailed field measurements for was 20.5 g/hour for larger hurricane lamps (n=14) and 14.4 g/hour for small ones (n=2). On a power basis, this translates to about 250 W and a luminous efficacy of about 0.1 lm/W (compared, for reference, to ~75-100 lm/W for efficient solar-powered CFL or LED light sources) on a primary energy basis.

Pressurized kerosene lamps ("pressure lamps") are the other prominent kerosene burning lighting technology we observed; they were in use by 13 of the 50 vendors as a primary lamp. Pressure lamps burn about 10-20 times brighter and consume fuel at a faster rate than hurricane lamps. The lighting service from pressure lamps is typically 50-75 lux at 1 meter, and the median kerosene consumption rate we measured was 70 g/hour Radecsky et al 2008), about 900 W on a power basis. The luminous flux output for the pressure lamps we measured was likely between 350 and 550 lm. The luminous flux output of pressure lamps has not been reported in the literature, but we can estimate it assuming that the ratio of luminous flux to illuminance for hurricane lamps is the same (i.e., the luminaire efficiency and luminous distribution for the two lamp types is the same). Mills (2003) reported that the ratio was 7.14 for hurricane and pressure lamps. The luminous efficacy of pressure lamps is better than hurricane lamps, about 0.5 lm/W, but users end up paying substantially higher operating costs because pressure lamps cannot operate at lighting levels as low as those of hurricane lamps.

The vendors we surveyed tended to use their lamps for about 2 hours each night in a business context, although those in Mai Mahiu tended to operate for longer (median use 2.5 hours) and Karagita for shorter (median use 1.8 hours). The vendors in Karagita operated for a shorter time due to security concerns in the area. Anecdotes from people familiar with the area indicated that Karagita was heavily impacted by the post-election civil violence that occurred in early 2008 and that peoples' ongoing security concerns led them to avoid public areas after dark, leading to truncated market hours compared to normal. Additionally, many vendors used their fuel-based lamps to illuminate their homes after business hours.

The cost of fuel based lighting to the vendors we worked with was quite high on an annual basis. Figure 9 shows the distribution in self-reported annual fuel costs based on primary fuel-based lighting type. We made the estimates based on vendors' responses to questions about their primary lamp type and daily fuel purchase, as described in the caption. Pressure lamps are the most costly to operate, followed by hurricane, tin lamps, and candles.

Figure 8: Types of fuel-based lighting we observed in use with the number of vendors using each technology.

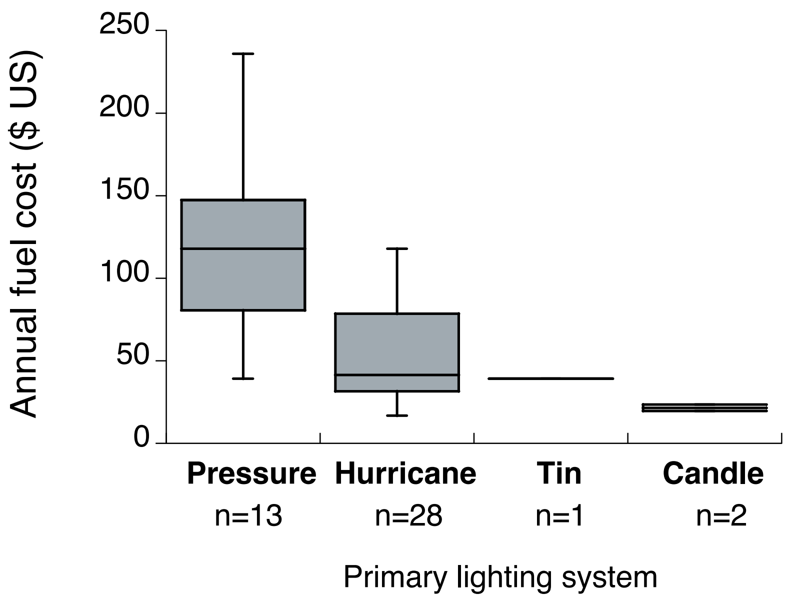

Figure 9: Annual fuel cost estimates in the business context for each of the four fuel-based lighting types we observed. The estimates are based on user's estimate of their daily fuel costs (originally in Kenya Shillings, converted to $US), their estimate of the relative amount of time that the lamp is used at their business versus elsewhere, and a de-rating factor of 30% based on our findings related to how accurately the night market vendors we worked with tend to estimate their daily fuel costs. Three vendors who used hurricane lamps were not included in this plot because they were unable to estimate their daily fuel cost during the survey.

Baseline Impressions on Lighting Technology

We asked each of the vendors in the baseline survey questions about their satisfaction with their current lighting technology (which was low) and interest in LED alternatives (which was high). A follow-up to each question asked respondents to identify factors that determined their dissatisfaction / interest. The results from the series of questions are summarized in Figure 10.

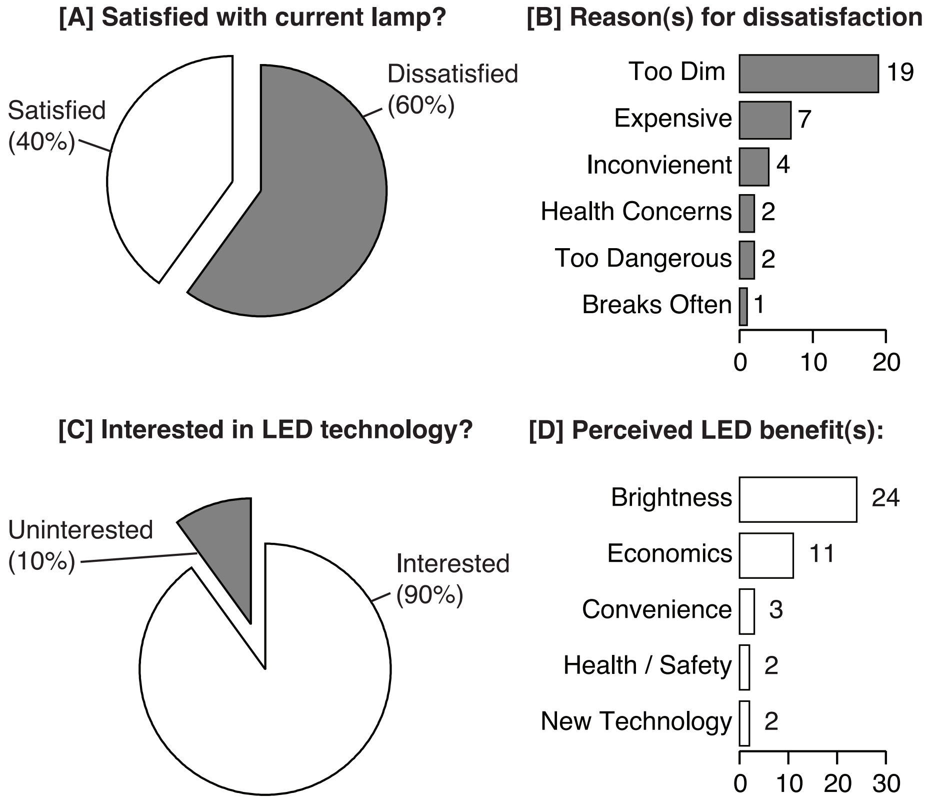

Figure 10: Summary of baseline survey results (n=50) related to [A] users' satisfaction with their baseline lighting technology and [B] reasons for their dissatisfaction if applicable, where people could list multiple reasons; [C] interest in LED alternatives and [D] perceived potential benefits of LED technology, if they had specific ones in mind, based on their past experience or on the sample products we showed and described to them.

Only 40% of fuel-based lighting users were satisfied with their lamps. All users who use electric lamps, 77% of the pressure lamp (order of magnitude higher brightness than hurricane lamp) users, and only 23% of hurricane lamp users were satisfied. In spite of the higher operating costs reported by pressure lamp users, the majority was satisfied, indicating that they have made a choice to pay more for higher quality lighting because they can afford to and feel it is cost-effective for their business.

Sixty percent of the night market vendors we talked to were dissatisfied with their current lamp. Of the 31 hurricane lamp users, 77% were dissatisfied, comprising the majority in the "dissatisfied" group. Of those who were dissatisfied, insufficient lighting service ("too dim") was the most common complaint, followed by high operating costs. Inconvenience, health, safety, and durability concerns were mentioned also, but infrequently. Three pressure lamp users were dissatisfied, two because of the high operating costs and even one who operated a butchery because it was "too dim" for the application (sharp knives, multiple cutting stations spread over ~10 m^2).

The vast majority (90%) of vendors were interested in exploring LED alternatives to their baseline lighting technology. Many of them were already somewhat familiar with LED lighting; 32 of 50 had some experience with LED lighting, 30 of whom were familiar with the LED flashlights that are rapidly taking over market shares in Sub-saharan Africa (Johnstone et al. 2009). The reasons people cited for their interest in LEDs mirrored the complaints of dissatisfied fuel-based lighting users. Brightness and lower operating costs were the top two perceived benefits from LED technology, followed by convenience, health, and safety benefits.

Adoption of LED Lighting by Night Market Vendors

Fourteen vendors out of the 23 were offered the opportunity chose to purchase a grid-charged LED lamp, many with financing offered by the research team. Their purchase choices reflected the charging options available in the peri-urban town centers, where the grid was present but access was limited by high connection costs, higher initial costs for solar charging, and concerns about security.

All but one vendor chose to purchase the lamps with an AC/DC adapter for accessing grid electricity from our research team for 700 Ksh (~$US 10.75) and one of the vendors chose to purchase a solar module along with the lamp for an additional 800 Ksh (~$US 12.30). There were several reasons. Some vendors had easy access to electricity, either with a grid connection at home, at a friend's home, or from an existing solar home system. For them, the additional expense of a solar module did not make sense from a financial standpoint. Other vendors intended to pay a fixed fee for charging services at a shop – a common enterprise in Kenyan towns that has grown with the mobile phone industry and a transaction the vendors were comfortable with. At those shops, the vendors paid 20 Ksh (~$US 0.25-0.30 depending on the exchange rate) for each recharge. This amounted to paying approximately 10 $US/kWh, two orders of magnitude higher than the marginal retail rate for commercial customers, about 0.14 $US/kWh. The overhead costs and margin for the retailer made up the difference.

Financing the initial costs of the lamps was a critical issue for many of the vendors we worked with. We offered zero-interest financing (half up front, half in one month) to the vendors after their requests for credit and nine of the fourteen used it to purchase their lamp. The repayment rate was 100%, but several vendors took longer than one month to pay. In practice, the financing model we offered would obviously not be sustainable on free market terms. Our experience lends credence to the importance efforts to expand end-user financing for off-grid lighting. However, the time line on which we asked vendors to make purchase decisions was on the order of 2 weeks. We estimate that their daily income was between 50-200 Ksh, so the 700 Ksh initial cost of the lamps we offered would amount to between 25-100% of their income during the decision period. With that in mind, it is sensible that many vendors required financing to make their purchase. Had our "business model" been less time sensitive (e.g., if we had set up a long-term shop to sell lighting products), the interested buyers may have been able to save ahead to make their purchase over several weeks and months, as needed, and some may not have required financing to make a purchase.

The Choice to Buy Off-Grid LED Lighting (or Not)

The vendors who were offered LED lighting products for sale (23 of them) faced a decision about whether the technology was affordable, appropriate for their needs, and likely to work out well over time.

One factor that may have influenced their purchase decisions was the high time value of money (i.e., the people we worked with were generally "cash poor" and acted as though they had high personal discount rates). The cost of fuel-based lighting is driven mainly by ongoing fuel purchases, which stands in contrast to the cost of electric lighting systems which can have ongoing costs that range from zero (in the case of solar charged products, aside from battery replacements) to high percentages of the total (in the case of users who pay for each recharge at a shop, typically once or twice a week). Switching from fuel-based to a solar-charged lighting system represents a paradigm shift in one's economic strategy for accessing lighting in addition to the technology shift that is readily apparent – essentially a shift from small daily purchases (like a lighting subscription) to a single outlay up front (or with short-term financing) for several years of lighting service. For those who are cash-poor, it can be difficult to abandon the economic model of accessing lighting where the initial cost of equipment is lower and the outlay on any given day is modest.

Discount rates aside, clearly there are other concerns that lead to a vendors' decision to purchase or not purchase an LED lamp. The vendors we worked with operated cash businesses, but not ones with seasonal swings in income that were apparent to us. The vendors we worked with had a net income of 50-200 Ksh per day[1], so an LED lamp would represent four to fourteen days of income for them. Depending on their other cash obligations, it may have been simply too difficult to pull together the cash necessary to pay for a lamp regardless of any desire to save money by switching to LED lighting. The optional financing was attractive in this regard.

Finally, any consideration of new technology adoption includes the criterion, "Will it work?" Flame based lighting has worked reliably, albeit at a high economic, health, and environmental cost, for millennia. Quality issues are a particular concern for LED lighting as it has emerged in the African market. A recent set of studies by Lighting Africa showed that inexpensive LED torches like the ones used by some of the vendors we surveyed in 2008 have become ubiquitous (Johnstone et al. 2009; Harper et al. 2013) and are of extremely low quality (Mink et al. 2010). A series of Lumina Project reports focused on LED torches by Tracy et al. (2009 and 2010) showed that nearly 90% of LED torch users—some in the towns in which the current study was being conducted--experienced quality-related problems over a six-month period and that there was a significant demand for higher quality LED torches in the market. Because most African consumers will likely experience LED technology first with a low-quality torch, there is a significant market spoilage risk.

We found that in the limited sample size of our study, previous experiences and familiarity with LED lighting, primarily flashlights, had a statistically significant negative impact on users' decision to purchase an LED gooseneck lamp from us, in spite of the one-year warranty we offered (warrantees are also ostensibly offered on the packaging of many low quality products in general in Kenya, with limited recourse to the consumer to service them).

Figure 11 illustrates our findings related to purchase choice and shows LED lighting familiarity by type for night market vendors in Mai Mahiu and Karagita. Of the 23 vendors who were offered

[1] The estimate is not based on survey questions; we did not want to color the interaction by asking about income. We estimated based on casual observation of their business and local rules of thumb.

and LED lamp for sale, eleven were familiar with the technology and twelve were not. Ten of the eleven were familiar with LED torches, four were familiar with strip or array style LED lighting; a similar pattern of familiarity was observed in the larger population of night market vendors, where 32 of 50 (64%) were familiar with LED lighting, 30 of whom were familiar with flashlights. Out of the eleven vendors who were familiar with and offered the choice to purchase an LED task light, only three (27%) chose to purchase. Out of the twelve who were unfamiliar, eleven chose to purchase (92%). A linear regression model (detailed in the Appendix) also indicates that prior familiarity with LED lighting is the largest magnitude and most statistically significant factor that predicted the purchase choice.

Our results show that a market spoiling effect exists from exposure to existing LED products – primarily flashlights - among the night market vendors we engaged with. As Table 4 shows, we found no overlap between the 95% confidence intervals on the estimated proportion of those who will purchase improved LED lighting products for two groups: those who are and are not already familiar with lower-quality existing LED lighting products.

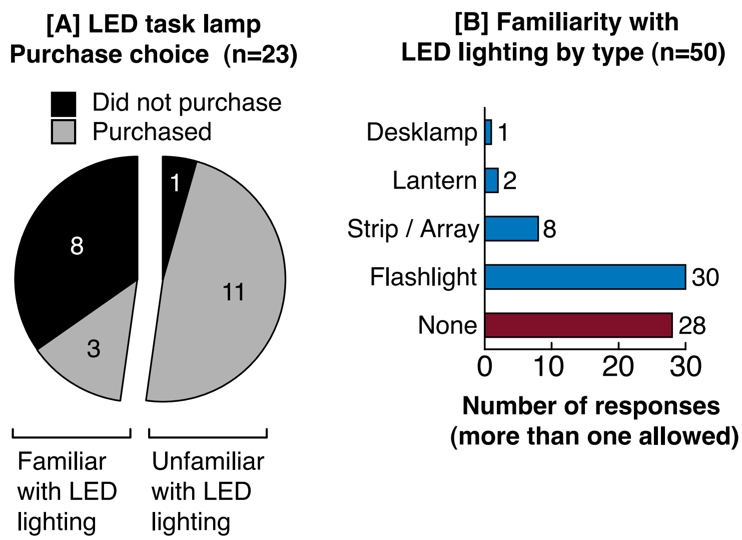

Figure 11: LED task light purchase choice for those who were given the option (n=23) and familiarity with LED lighting by type for the night market vendors who were surveyed (n=50). Of the 32 (64%) of all (n=50) night market vendors who were familiar with LED lighting, 30 of 32 (94%) were familiar with flashlights.

Table 1: Proportion of night market vendors who purchased and LED task light during our study grouped by their previous familiarity with LED lighting. The confidence intervals were estimated based on tabulated values (Beyer 1968). The estimated significance level for the difference between the familiarity factors is p=0.0028 using Fisher's Exact test for Count Data (implemented in R using package:stats) which indicates the null hypothesis that people are not influenced by prior experience can be rejected at a high level of significance.

Familiarity level	95% Lower Limit	Sample proportion who chose to purchase	95% Upper Limit
Familiar w/ LED lighting (n=11)	6.0%	**27.3%**	61.0%
Unfamiliar w/ LED lighting (n=12)	61.5%	**91.7%**	99.8%

First Year of Modern Lighting

The vendors who purchased LED lamps did not uniformly adopt them and eliminate kerosene use at their businesses. Through ongoing surveys and observation our team observed a mean kerosene offset of 50% from adopting the LED task light.

We asked vendors on each survey (0, 6, and 12 months into the study) what their primary light for the business was, and our field agents made a series of randomly timed nighttime observations of the night market vendors of Mai Mahiu in the fourth month to check adoption rates. We included the nightly observational study as a check on vendors' responses; we wanted to avoid the phenomena of vendors "telling us what they think we want to hear" regarding their adoption of LED lighting. Each vendor was observed 24 times over the course of a week, 240 total observations among the 10 vendors in Mai Mahiu who purchased LED lamps. Figure 12 shows the results of the surveys and observations. Note that there was some attrition over time as we lost track of vendors who moved during the study. Overall, the adoption rate of LED lighting as a primary business lighting system was about 60% over the yearlong study period.

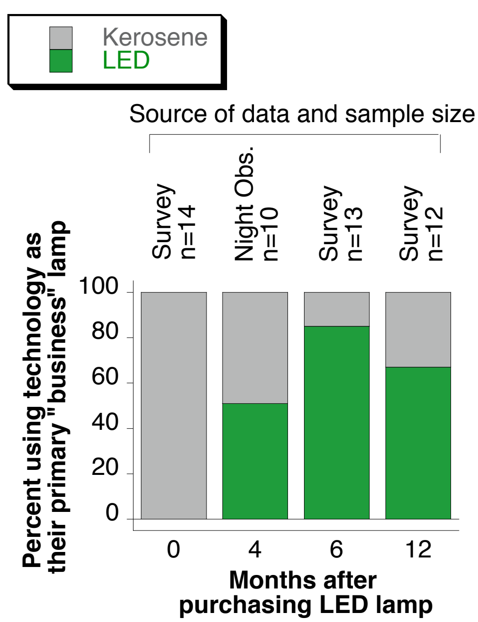

Figure 12: Adoption rates of LED lighting at night market businesses by vendors who purchased LED products from us at 0, 4, 6, and 12 months after the beginning of the study.

The vendors who used LED lamps as the primary lighting source in the night market reported using them for approximately 2 hours each night at their businesses and an additional hour at home. Table 2 below shows their daily use estimates from both data-logger monitoring and surveys at 6 and 12 months. The data-logger records do not distinguish between business and home use, but we asked vendors to disaggregate their use in the surveys. The agreement in the mean total use per day between the surveys and data-logger records lends credence to vendors' estimates of how long they use their lamps. Additionally, their estimates of daily run time reconcile well with the run-time of the lamps (10 hours) and how often users reported they typically recharged, a median answer of every three days. The median number of days per recharging cycle we observed using the data-loggers was four days. Based on the apparent quality of the daily use data provided by the vendors, we have confidence in the overall ability of vendors who use off-grid lighting to estimate their hourly use patterns and charging frequency.

Table 2: Hours of LED lighting use reported by vendors and observed with embedded data-loggers.

Estimate Type	Business Use (hours/day)		Home Use (hours/day)		Total Use (hours/day)	
	Mean	*Median*	*Mean*	*Median*	*Mean*	*Median*
Data-logger records*	--	--	--	--	2.5	2.2
6-month Survey (n=11)	1.8	2	0.8	1	2.6	3
12-monthy Survey (n=8)	1.6	1.75	0.8	0.25	2.4	2.5

*351 days of sampling between months 2 and 7

Solar Energy Concerns for Vendors

After six months we gave solar modules to each of the vendors who was still participating in the study; it was clear by then that none of them intended to purchase one from us and we were interested to see how (and if) their charging practices would be influenced by the ownership of a solar module. At the six-month point, nine vendors typically recharged at a fee-based shop, three had access to grid connections at their home or that of a friend, and one used a solar home system with a DCDC converter to recharge. In spite of the "free" nature of solar charging, many vendors chose to continue paying for charging services from fee-based recharging shops after receiving a solar module. Only two vendors adopted solar charging as their primary method. The reasons vendors gave for not adopting solar charging included security concerns (they did not want to module to be stolen), perceptions of ineffectiveness (they felt that grid charging resulted in a more "full" charge), and the inconvenience of needing to tend the solar module. Some vendors did choose to solar charge, noting that their costs were lower. The vendors who used solar charging successfully tended to recharge each day, while those who did not reporting that they attempted to use solar charging like grid charging (i.e., they put it out to charge when the state of charge was low instead of every day). The vendors' use of solar charging in this context cannot be taken as representative of how solar charging might be treated in the wider market because the modules were gifts rather than a purchase and the vendors had access to alternative charging means that they successfully used for six months prior to having a solar option. People who live far off-grid would face much different circumstances. However, concerns about security near solar charging points to the fact that there are non-monetary costs to those who use portable solar lighting products and have to spend time and energy managing the charging process and ensuring their lamp and/or solar module is not stolen.

Impacts of LED Lighting Technology Over Time

We divided the vendors who were tracked over one year into two groups: the vendors who purchased LED lighting ("LED purchasers") and those who did not ("LED abstainers"). By tracking both, we maintained a pseudo-control group (albeit a self-selected one), the LED abstainers, as a basis for comparison. While there were differences in the baseline for each group in terms of mean and median daily costs and kerosene consumption, there was no statistical significance to the difference (i.e., the groups were not distinct in terms of their kerosene consumption to begin with, and by extension daily expenses, GHG contributions, etc.). Table 1, below, shows the time-series results for several metrics.

For vendors who used grid-charging for their lamps it was important to account for their electricity consumption. The Kenya grid includes both hydroelectric and oil-burning thermal plants that can operate on the margin (Kenya National Bureau of Statistics 2008). We assume the additional load from grid charging lamps is equally likely to come from either hydroelectricity or thermal plants that have an efficiency of 33%; both sources are assigned 10% line losses. This results in an estimate for the average marginal primary energy intensity of 6 MJ/kWh. Based on the measured charging efficiency of the AC charger of 21% and assumed battery efficiency of 70%, the lamps we offered required 25 Wh of grid electricity for each charging cycle. The median observed recharging rate for lamp users was once every three days.

Table 3: Summary of expenditures and energy use for lighting in business contexts for LED purchasers and abstainers over a 12-month study period.

		LED Purchasers			LED Abstainers		
	Month	mean	median	% change in mean	mean	median	% change in mean
Daily Expenses (Ksh/day)	0	16	14	n/a	19	22	n/a
	6	10	7	-39%	13	14	-31%
	12	7	5	-58%	12	13	-39%
Kerosene use (mL/day)	0	138	138	n/a	158	82	n/a
	6	68	0	-50%	116	91	-27%
	12	89	0	-35%	175	171	11%
Grid electricity use (Wh/day)	0	0.0	0.0	n/a	0.0	0.0	n/a
	6	7.3	8.3	Inf	0.0	0.0	0%
	12	6.9	5.0	Inf	0.0	0.0	0%
Primary Energy use (MJ/day)	0	5.6	5.6	n/a	6.5	3.3	n/a
	6	2.8	0.1	-50%	4.8	3.7	-27%
	12	3.4	0.1	-40%	7.2	7.0	11%
Sample Size	0	13			7		
	6	13			7		
	12	13			4		

The price volatility in the kerosene market[2] (falling prices) combined with the fact that many end-users paid to recharge their lamps essentially eliminated much of the potential economic benefit from switching to LED lighting over the course of the study; both user-groups thus experienced falling costs for lighting overall (60% reduction for the LED purchasers and 10% reduction for the non-purchasers). The expenses for fuel and ongoing costs did not drop to zero for the LED purchasers because several of them continued to use kerosene lamps at their businesses either solely or in combination with the LED lamp. Furthermore, those who did not choose to purchase or use solar charging for their lamps paid a fee to recharge (~$US 0.25 each time).

The mean kerosene consumption for the LED purchaser group was reduced on the order of 50% over the year. For the non-purchasers, their consumption over the study period increased by 70%, which was likely due to falling fuel prices. In spite of the increased use their costs fell on average from the rapidly falling prices.

The failure to fully offset kerosene by LED lamp purchasers occurred for both hurricane and pressure lamp users but in different ways for each group. For hurricane lamp users, a typical pattern was for them to continue to use the hurricane lamp occasionally in addition to the LED lamp. For pressure lamp users, those who used the LED lamp at their business typically did not also use the pressure lamp (which is two orders of magnitude brighter), but there were also two vendors who purchased and LED lamp for sole use at their household. If the lights we had offered were bright enough to meet their needs or if we had offered brighter alternative lights to them, it is likely that they would have switched as well. Both of them reported trying the LED lamp at their business and concluding it was not bright enough, which indicates a diversity of needs in terms of lighting levels even among night market vendors. The degree of market segmentation in the wider off-grid lighting market also includes very many levels of service need and ability to pay.

The most notable result from our analysis of the time-series data is that the primary energy requirements for those who purchased LED lights were not reduced to zero. While approximately 60% of those who adopted an LED light completely eliminated their use of kerosene, the others continued using kerosene at the same or slightly higher rates. For the purposes of uncertainty assessment, we assume the estimate for the fraction of kerosene that is still in use by the average user is 0.5, but with a triangular distribution of likely values for individuals with a maximum offset of 5% more than the baseline, median of 100% of the baseline, and minimum of a 50% *increase* above baseline, which roughly corresponds to the distribution of observations in our study and results in a mean displacement of 50%. Figure 13 shows the dynamics of how adoption leads to decreases in the mean consumption for the group that adopted LEDs and a mean increase in consumption for those that did not adopt.

[2] One vendor mentioned that being shielded from price volatility was a positive aspect of using LED lighting. She recounted that there was a temporary price spike in kerosene due to national shortages in month 5 of the study and she was glad to have been unaffected by it.

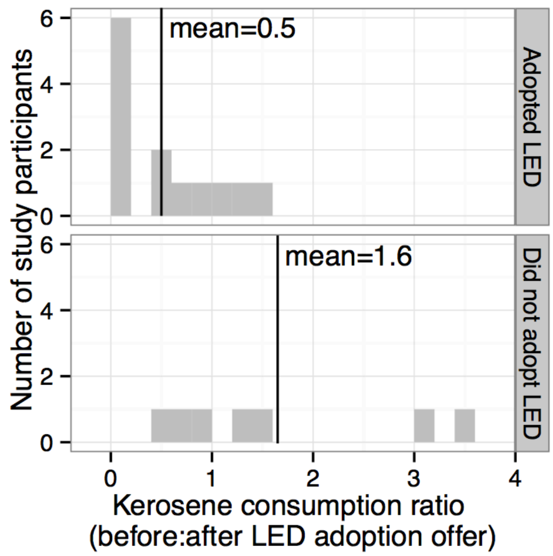

Figure 13: Kerosene consumption ratios before and after LED adoption choice for those who did and did not adopt.

We should stress that the population we worked with has special needs and were nested in a particular economic and geographic context. They may not be representative of the larger consumer market for in-home off-grid lighting, but the implication for emissions reduction assumptions around LED lighting is that 100% offset may not be likely to be a defensible choice for other products of similar size (a desk lamp). It is possible that design changes (e.g., a brighter light with longer run time) may lead to higher levels of offset. Indeed, subsequent studies using better-performing systems have shown larger offset rates.[3]

Conclusions

Our work in the 2008-2009 market for off-grid lighting in two towns in Kenya illustrates the importance of locally grounded information to support emerging markets. One might expect the vendors we worked with to be a relatively homogenous population—they live in the same towns, have similar occupations and income streams, etc.—but we observed a great deal of diversity in their approaches to accessing lighting for their businesses. There was a range of baseline technology in use, with annual costs ranging from about $20 to $200 for fuel purchases. These costs varied across vendors and also are strongly influenced by volatile world oil prices, leading to cost uncertainty for users. More than half the people who had the option purchased an improved off-grid LED light as part of the research study, and the most significant and largest factor predicting the purchase was *lack of* prior experience with low-quality LED lighting, suggesting market spoiling. Additionally, reflecting the diversity in incomes and lighting needs, many vendors who did purchase improved LED lighting continued to use fuel-based lighting (while others did not). This increase in lighting service that is important to account for in any development impact assessment for off-grid lighting where there is pre-existing suppressed demand due to economic hardship or fuel scarcity.

[3] See discussion on LuminaNET: http://luminanet.org/forum/topics/how-much-fuel-or-batteries-are-actually-saved-by-improved-off-gri

There were also important similarities among the vendors in the study. Most (60%) were dissatisfied with their baseline fuel-based lighting, particularly those who used hurricane lamps, which have lower output and efficacy (along with lower operating costs) than the pressure lamps that some vendors used. Those who were dissatisfied cited brightness as a key factor. Additionally, in spite of the revealed skepticism engendered by market spoiling, 90% of the vendors we surveyed were interested to learn more about improved LED lighting. Targeted consumer education and exposure to good-quality LED lighting that is owned and operated by friends and neighbors could gird the market against spoiling from low-quality LED lights.

Beyond the results for these vendors, which are a useful case study on the dynamics of the market, we identified several methodological approaches that are useful for understanding the market more broadly. Specifically, a combination of "true cost of kerosene" estimates and high frequency or short term recall surveys provides a useful baseline on fuel-based lighting use. Because these methods do not require detailed surveys or explanation by end-users (beyond the type of lighting they use and how much they spent on fuel in the last day/week) it may be possible to leverage the ubiquity of mobile phones to conduct automated, high resolution surveys via SMS (i.e., directly back and forth with end-users) to improve the data on the baseline fuel-based lighting market. We recommend pilot testing an automated approach with follow-up in person surveys to verify the results. If this approach is useful it would be a powerful tool for targeting market interventions and supporting research.

In addition, in spite of the technical difficulties we experienced with the first-generation integrated data-loggers employed in the study, the data we obtained showed the potential value from high-frequency use-pattern data for researchers, product developers, and institutions supporting the market. The value is magnified when those data are combined with good analytics and outreach to consumers via mobile phones or other modern communications. From simple measurements of it is possible to make estimates and inform interventions that address three important factors:

- **The effectiveness of users' solar panel placement**, by comparing the solar energy input from a number of solar modules in close geographic proximity (or compared to a reference pyranometer). Some users place the module in full-sun exposure while others often do not place it outside until the late morning or place it in a location prone to shade. This would be an important factor for product design and estimates of performance since any losses from ineffective placement effect performance just like any other inefficiency. Unlike other efficiency losses, this one can be corrected with user education, either through feedback from the device or with targeted outreach from a project developer or institution. With good data, it would be possible to effectively target the interventions.
- **The patterns of daily use**, by observing the current discharged from the battery (and further disaggregation by load type if appropriate). These patterns would inform product design and could lead to predictive messages targeted to consumers whose historical use patterns indicate they may face an energy shortage due to upcoming weather events or seasonal variation in solar energy.
- **Product maintenance issues,** by identifying diminished performance that cannot be explained by patterns of use or a lack of solar energy, or more starkly based on products that simply go out of service. Outreach to users who have a device with likely issues could prevent backsliding to kerosene lighting. The same data would be useful for tracking development impacts of off-grid lighting by verifying continued use.

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Appendix

Regression Model for LED Lamp Purchase

We used an ordinary least squares regression model to identify factors that may be significant determinants for the purchase decision of individuals. We chose independent variables for the model that would explain geographic preference (Town), proxies for income (Nightly Fuel Cost and Shop Architecture), proxies for lighting needs (Shop Architecture and Lamp Type), and a market spoiling proxy (Familiarity with LED Lighting). We found that the variable with the greatest influence and most statistical significance was the market spoiling proxy. Additionally, income and lighting needs seem to factor into the decision. People with high fuel costs were more likely to purchase a lamp and people with the need to light a small walk-in shop (which typically have more space to illuminate than other shop types) were less likely to purchase an LED task light.

LED Lamp Purchase Decision Determinants

	Dependent variable: Purchased Improved LED Light
Architecture:Market Stall	0.251
	(0.228)
Architecture:Market Stall with Building Behind	-0.116
	(0.200)
Architecture:Other	-0.172
	(0.309)
Architecture:Small Shop (walk in)	-0.739**
	(0.272)
Nightly Fuel Cost	0.032**
	(0.012)
Town (mmu)	-0.176
	(0.199)
Lamp Type (Pressure)	-0.034
	(0.204)
Familiar with LED Lights	-0.903***
	(0.228)
Constant	0.535*
	(0.276)
Observations	23
R2	0.798
Adjusted R2	0.682
Residual Std. Error	0.281
F Statistic	6.894
Note:	*p<0.1; **p<0.05; ***p<0.01

Lumina Project 2008 Task Lamp Characteristics

The LED lamps we offered for sale were modified versions of a commercially available lamp (the Barefoot Firefly Task Light). They are a task-style lamp with 12x 5mm white LEDs on a flexible gooseneck that plugs into a base unit that contains batteries and circuitry. We provided a 6 foot extension cable to allow the gooseneck to be located remotely from the base. The battery pack was 3x 1300 mAh rated NiMH cells with a nominal voltage of 3.6 V. A charging circuit prevented overcharge, but did not have a low-voltage disconnect to prevent deep discharge of the batteries. In addition, each lamp was outfitted with a micro-data-logger designed to monitor the battery current and voltage for estimating use patterns.

We offered two charging options: a grid (230 V 50 Hz) charger or a 1 W solar module. The grid charge option was priced at 700 Ksh, the solar charge option was priced at 1500 Ksh. None of the vendors chose to purchase the solar option; they all either paid a fixed fee (normally 20 Ksh) to charge or had alternative AC charging arrangements, like grid access at home, a solar home system, etc.

We used a "lamp discharge" test to characterize some important performance characteristics of the lamps as they were deployed in the field. The test consists of discharging a fully charged lamp while data-logging illuminance at a fixed distance, battery current and battery voltage. The discharge is considered to be over when the illuminance reaches a value of 50% of the initial (peak) illuminance. Table 4 includes the key results from the test.

Table 4: Lamp discharge test results summary for Lumina Project lamps as deployed.

Performance Metric	Value
Useful Battery Capacity (mAh)	1,000
Useful Battery Energy (Wh)	3.7
Lighting Service Duration (h)	10
Peak Illuminance at 1 meter (lux)	14
PV Power (W)	1

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